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Air Force Workshop on Optimal Design and Control

Final Technical Report on AFOSR Grant F49620-97-1-0264

for the period 1 April 1997 - 31 December 1997

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This report contains a summary and highlights of the work funded by the Air Force under AFOSR Grant F49620-97-1-0264, titled " Air Force Workshop on Optimal Design and Control ". This effort was conducted by the Air Force Center for Optimal Design and Control (**CODAC**), during the period 1 April 1997 - 31 December 1997. The Center planned, organized and ran a workshop in Washington, DC from 30 September through 3 October 1997. The workshop was attended by sixty-six participants with thirty-six technical presentations.

The objectives of the workshop included an assessment of current research efforts in optimal design, an evaluation of Air Force needs and identification of future directions in optimal design.. The speakers, including twenty invited leading researchers, covered a variety of topics including: Sensitivity Equation Methods, Adjoint Methods, Automatic Differentiation, Optimization Theory and Algorithms and Engineering Design Applications. Twenty-two of the technical papers have been assembled into a Proceeding volume, to be published by Birkhauser-Boston. A second volume assessing the state-of-the-art and future directions will also be published by Birkhauser-Boston

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Summary

This Grant provided partial support for a workshop on Computational Methods for Optimal Design and Control that was held in Washington, DC, 30 September – 3 October 1997. The basic objectives of the proposed workshop were

1. to assess the current status of research in optimal design as it applies to Air Force problems,
2. to bring together the diverse group of researchers in this area in order to share and compare the different approaches to inverse design and
3. to provide an evaluation of Air Force needs and future directions in computational tools for optimal design.

To meet these objectives approximately twenty internationally recognized leaders were invited to present status reports on their basic research programs. With the addition of contributed talks a total of thirty-six presentations were made. In addition, each attendee was asked to provide a brief hand-written summary of issues and challenges. This information was used to identify future directions and to draft a report analyzing the challenges posed by future Air Force problems. Two volumes have been produced as a result of the workshop. One volume is a proceedings containing twenty-two of the scientific papers. The second volume provides an assessment of the state of the art and an analysis of future directions in the field. Both volumes are being published by *Birhkauser - Boston*. The Proceedings volume is in-press and will appear in April 1998. The front-matter from this volume is included as an Appendix. The Future Directions volume is in editorial review and will be available later in the year.

1 Introduction and Overview

Many of the most challenging engineering design applications currently facing the Air Force and the aerospace industry may be formulated as optimal design or inverse problems. These applications include, but are not limited to, structural optimization, nozzle and shape design for wind tunnel testing, wing/body design, inverse design for improved stealth, general shape optimization for flow management, combustion and high speed flows. It is this universal range of applications that has generated a demand for new optimization-based computational tools. The widespread demand for such tools has generated a tremendous surge in research on computational methods for optimal design. During the past decade, this work has produced numerous new methods and lead to the development of a wide variety of computational algorithms.

In order to address these fundamental questions, the workshop brought together sixty-three participants from a wide spectrum of research disciplines including: optimization theory, control theory, computational mechanics, structural dynamics, computer science, computational fluid dynamics, numerical analysis and computational physics.

The Conference Program is included as Appendix A and a list of participants is included as Appendix B. The front-matter of the Proceedings volume, to be published by *Birhkauser - Boston*, is included as a final Appendix.

2 Technical Areas

The thirty-six presentations at the Workshop covered a variety of themes including:

- Sensitivity Equation Methods
- Adjoint Methods
- Automatic Differentiation
- Optimization Theory and Algorithms
- Engineering Design Applications

2.1 Sensitivity Equation Methods

There are a variety of approaches to the formulation and solution of engineering design problems. We concentrate here on a class of problems which can be formulated as mathematical optimization problems. When used as a paradigm for engineering design, the state sensitivities (derivative of the state with respect to the design parameters) play two key roles. They provide gradient information for the optimization algorithm and sensitivity information for analysis of a particular design. Therefore, efficient computation of accurate sensitivities is a major requirement of any design tool.

2.2 Adjoint Methods

For many applications the adjoint equation approach is an attractive alternative to the SEM for the computation of gradients. While the adjoint equations are used for various distributed optimal control problems, many issues are still subject to active research. One issue that arises repeatedly is the issue of consistency and adjointness: In many applications, discretizations of the infinite dimensional adjoint equation are not the adjoint equations of the discretized problem and vice versa. Additional research issues arise that concern the correct mathematical setting of the problem, formulation of the adjoint equation, in particular boundary conditions for the adjoint, and the existence of the adjoints.

2.3 Automatic Differentiation

In many applications the direct or analysis problem results in software package capable of predicting the system's performance for given values of the design parameters. In such setting it is natural to adopt a computational viewpoint that focuses on exploiting the existing simulation code. Thus the basic idea in automatic differentiation is to produce an auxiliary computer code that will compute the sensitivity of the original code to changes in data. The idea is very attractive in many industrial applications wherein complex *legacy codes* have been developed for the direct problem. OSR has previously sponsored a workshop in this area in January 1991.

2.4 Optimization Theory and Algorithms

Design problems can be formulated as optimization problems in a variety of ways, among these the black–box–formulation and the all–at–once formulation are extreme points. In many cases the smoothness (or lack thereof) of the cost and constraint functionals is a key issue. For smooth problems sequential quadratic programming (SQP) methods with trust–region strategies are among the preferred approaches. However, many *legacy* codes for simulating the behavior of engineering systems include features which induce non-smooth dependence on design parameters. Thus, a number of contributors addressed such issues. Finally, in many engineering disciplines one has a spectrum of available analysis models/tools. These may range from simple inexpensive database-interpolation methods, to sophisticated CFD simulation codes. Several speakers addressed issues related to model-management in the context of optimization.

2.5 Engineering Design Applications

The motivation for the tool-development described above stems from a variety of applications in aerospace design. One aspect of these problems is their multidisciplinary nature. In a comprehensive design for transport aircraft, for example, structural, aerodynamic, propulsive and flight-control requirements must each be considered. Several speakers addressed these concepts.

Workshop Program

Tuesday Morning, 30 September 1997

08:00 - 08:45	Registration
08:45 - 09:00	Welcome: Salon A
	Session TU-AM: Salon A **Session Chair: Major Scott Schreck**
09:00 - 09:45	Roland Glowinski University of Houston *Some Fundamental Issues in Optimal Design/Shape Optimization*
09:45 - 10:30	Ekkehard Sachs Universitat Trier *New Numerical Methods in Optimal Control*
10:30 - 11:00	Coffee Break: Salon A
11:00 - 11:45	Max Gunzburger Iowa State University *Sensitivities and Adjoints in Computational Methods for Optimal Flow Control*

Tuesday Afternoon, 30 September 1997

	Session TU-PM: Salon A **Session Chair: Eugene M. Cliff**
13:15 - 14:00	Andrew Conn T.J. Watson Research Center, IBM *Recent Progress in Unconstrained* *Nonlinear Optimization Without Derivatives*
14:00 - 14:45	Thomas Coleman Cornell University *Automatic Differentiation is NOT Automatic* *(When Applied to Inverse Problems in Optimal Design)*
14:45 - 15:15	Coffee Break: Salon A
15:15 - 16:00	Gal Berkooz BEAM Technologies, Inc *Optimization in Real World Engineering Design:* *Needs and Opportunities*
16:00 - 16:45	Jason Speyer University of California, Los Angeles *Robust Reduced-Order Controller of* *Transitional Boundary Layers*
16:45 - 17:15	Discussion

Wednesday Morning, 1 October 1997

	Session WE-AM-1: Salon B **Session Chair: John A. Burns**
08:00 - 08:45	Jaroslav Haslinger Charles University *Fictitious Domain Approaches and* *Global Optimization Methods in Shape Optimization*
08:45 - 09:30	Nicholas Zabaras Cornell University *Sensitivity Analyses and Adjoint Method Algorithms* *for the Design of Material Processes*
09:30 - 10:00	Coffee Break: Salon A
	Session WE-AM-2: Salon B **Session Chair: Belinda King**
10:00 - 10:30	Eyal Arian ICASE *MDO-A Mathematical View Point*
10:30 - 11:00	Matthias Heinkenschloss Rice University *Interior point SQP Methods for* *Distributed Control Problems*
11:00 - 11:30	Josip Loncaric ICASE *Sensor/Actuator Placement Via Optimal* *Distributed Control of Exterior Stokes Flow*
11:30 - 12:00	Arun Verma Cornell University *Automatic Differentiation and* *MATLAB Interface Toolbox (ADMIT)*

Wednesday Afternoon, 1 October 1997

	Session WE-PM: Salon B **Session Chair: John Dennis**
13:30 - 14:15	Allen Tannenbaum University of Minnesota *Visual Information in a Feedback Loop:* *A Control/Computer Vision Synthesis*
14:15 - 15:00	Eugene Cliff Virginia Polytechnic Institute and State University *An Overview of Research at the* *Center for Optimal Design And Control*
15:00 - 15:30	Coffee Break: Salon A
15:30 - 16:15	Jean-Paul Zolesio Institut Non Lineare de Nice *Shape Differential Equations*
16:15 - 16:45	Discussion

Thursday Morning, 2 October 1997

	Session TH-AM: Salon B **Session Chair: Terry Herdman**
08:00 - 08:45	John Dennis Rice University *Optimization Using Surrogate Objectives*
08:45 - 09:30	Anthony Patera Massachussetts Institute of Technology *Fast Bounds for Partial Differential* *Equation Outputs*
09:30 - 10 :00	Coffee Break: Salon A
10:00 - 10:45	Andrew Godfrey AeroSoft, Inc. *Using Sensitivities for Flow Analysis*
10:45 - 11:30	Karl Kunisch KFU Graz *Numerical Optimal Control for Navier Equations*

Thursday Afternoon, 2 October 1997

	Session TH-PM 1: Salon B **Session Chair: Bernard Grossman**
13:15 - 13:45	Robert Lewis NASA Langley Research Center *Sensitivity Calculations and the Adjoint Equations from a Nonlinear Programming Perspective*
13:45 - 14:15	Ajit Shenoy Virginia Polytechnic Institute and State University *An All-At-Once Approach to Airfoil Design*
14:15 - 14:45	Dominique Pelletier Ecole Polytechnique de Montreal *On Computational Issues in Using Adaptive FEM and the Sensitivity Equation Method*
14:45 - 15:15	Coffee Break: Salon A
	Session TH-PM 2: Salon B **Session Chair: Marc Jacobs**
15:15 - 15:45	Jeff Borggaard Cornell University *On Optimal Design in Forced Convection*
15:45 - 16:15	John Otto Massachussetts Institute of Technology *A Surrogate-Pareto Approach to Shape Optimization: Level-Set Based Geometry Description*
16:15 - 16:45	Belinda King Oregon State University *An Optimal Design Approach to the Construction of Practical Feedback Controllers*
16:45 - 17:15	Duane Knill Virginia Polytechnic Institute and State University *Efficient Implementation of Euler Solutions for Supersonic Aerodynamic Predictions in Multidisciplinary HSCT Design*

Friday Morning, 3 October 1997

	Session FR-AM-1: Salon B **Session Chair: Max Gunzburger**
08:00 - 08:45	C.T. Kelley North Carolina State University *The Simplex Gradient and* *Noisy Optimization Problems*
08:45 - 09:30	Bernard Grossman Virginia Polytechnic Institute and State University *Multidisciplinary Design Optimization* *of Advanced Aircraft*
09:30 - 10:00	Coffee Break: Salon A
	Session FR-AM-2: Salon B **Session Chair: Ekkehard Sachs**
10:00 - 10:30	Martin Berggren FFA, The Aeronautical Research Institute of Sweden *Optimal Disturbances in Boundary Layers*
10:30 - 11:00	Dawn Stewart Virginia Polytechnic Institute and State University *Projection Methods for Accurate Computation* *of Design Sensitivities*
11:00 - 11:30	Paul Hovland Argonne National Laboratory *Automatic Differentiation* *and Navier-Stokes Computations*
11:30 - 12:00	Jean-Francois Hétu National Research Council of Canada *Optimization of Industrial Forming Processes:* *Issues and Challenges*

Friday Afternoon, 3 October 1997

	Session FR-PM: Salon B **Session Chair: Nicholas Zabaras**
13:30 - 14:15	Ilan Kroo Stanford University *Optimal Design of Aerospace Systems–* *Architectures and Applications*
14:15 - 15:00	Antony Jameson Stanford University *Optimum Design of Airplane Wings* *in Transonic Viscous Flow*
15:00 - 15:30	Coffee Break: Salon A
16:00 - 16:45	H.T. Banks North Carolina State University *Identification Problems in Electro-Magnetics*
16:45 - 17:15	Closing Session: Dr. John Burns

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Proceedings Volume – Frontmatter

COMPUTATIONAL METHODS FOR OPTIMAL DESIGN AND CONTROL

Proceedings of the AFOSR Workshop on Optimal Design and Control
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CONTENTS

PREFACE

This volume contains the proceedings of the Second International Workshop on Optimal Design and Control, held in Arlington, Virginia, 30 September–3 October, 1997. The First Workshop was held in Blacksburg, Virginia in 1994. The proceedings of that meeting also appeared in the Birkhauser series on Progress in Systems and Control Theory and may be obtained through Birkhauser.

These workshops were sponsored by the Air Force Office of Scientific Research through the Center for Optimal Design and Control (CODAC) at Virginia Tech. The meetings provided a forum for the exchange of new ideas and were designed to bring together diverse viewpoints and to highlight new applications. The primary goal of the workshops was to assess the current status of research and to analyze future directions in optimization based design and control. The present volume contains the technical papers presented at the Second Workshop. More than 65 participants from 6 countries attended the meeting and contributed to its success.

It has long been recognized that many modern optimal design problems are best viewed as variational and optimal control problems. Indeed, the famous problem of determining the body of revolution that produces a minimum drag nose shape in hypersonic flow was first proposed by Newton in 1686. Optimal control approaches to design can provide theoretical and computational insight into these problems. This volume contains a number of papers which deal with computational aspects of optimal control.

The workshop was a gathering of engineers and mathematicians actively involved in innovative research in control and optimization, with an emphasis placed on optimal design problems governed by partial differential equations. Many difficulties arise when trying to implement approximation techniques for these problems. These difficulties range from computational issues, such as the accuracy, ease and efficiency of state/function and gradient calculations, to concerns about integrating calculations from several subdisciplines. For example, contributions concerning gradient calculations can be loosely broken into three categories: (i) Automatic Differentiation, (ii) Adjoint Methods and (iii) Sensitivity Equations Methods.

In many cases, a detailed solution of the full physics-based state equations (partial differential equations or large systems of ordinary differential equations) is expensive. However, reduced order models with varying levels of validity can often be used to develop optimal design strategies. Several articles describe techniques for managing models in optimization algorithms. Model management is also considered for the case where different disciplines must be integrated. Model uncertainty caused by coarse approximations of partial differential equations or by obtaining function evaluations through experiment can introduce unacceptable noise in the design objective function. Convergence of optimization algorithms for problems with model uncertainty is discussed by various contributors.

Many important optimal design applications can be formulated as shape optimization problems. Shape optimization leads to additional difficulties and often requires the development of special techniques to address complex theoretical and computational issues. These difficulties range from theoretical considerations involving the development of proper mathematical framework for the discussion of shape derivatives, to computational methods for efficient calculation, or elimination of mesh gradients. Sensitivity equation methods and fictitious domain approaches to these problems are found in various articles on shape optimization.

The diverse background and experience of the participants, ranging from academia, to industry,to government laboratories, lead to a variety of techniques to address these difficulties. Overall, it is clear that there has been significant progress in the development of new computational and mathematical tools for optimal design and control. Moreover, these tools are being applied to very complex systems and have important applications to aerodynamic design, fluid flows, materials processing, inverse design and feedback control. On the other hand, there are many theoretical and practical issues that have not been resolved, and when resolved, could lead to revolutionary advances in design and control methodology. During the workshop the participants submitted position papers that identified these issues and suggested future research directions to address these difficult problems. The conclusions based on these suggestions will appear in a follow-up volume.

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